# Programming Languages

Modules and Exceptions

CSCI-GA.2110-001
Summer 2012

# Modules

Programs are built out of components called modules.

Each module:

- has a public interface that defines entities exported by the module
- may include other (private) entities that are not exported
- may depend on the entities defined in the interface of another module (weak external coupling)
- should define a set of logically related entities (strong internal coupling)

# What is a module?

- different languages use different terms
- different languages have different semantics for this construct (sometimes very different)
- a module is somewhat like a record, but with an important distinction:
  - **record** $\Longrightarrow$ consists of a set of names called *fields*, which refer to values in the record.
  - **module** $\Longrightarrow$ consists of a set of names, which can refer to values, types, routines, other language-specific entities, and possibly other modules

# Language constructs for modularity

Issues:

- public interface
- private implementation
- dependencies between modules
- naming conventions of imported entities
- relationship between modules and files
- access control: module controls whether a client can access its contents
- closed module: names must be explicitly imported from outside the module
- open module: outside names are accessible inside module (no explicit import)

# Language choices

- **Ada** : package declaration and body, `with` and `use` clauses, renamings
- **C** : header files, `#include` directives
- **C++** : header files, `#include` directives, namespaces, `using` declarations/directives, namespace alias definitions
- **Java** : packages, `import` statements
- **ML** : `signature`, `structure` and `functor` definitions

# Ada: Packages

```
package Queues is
  Size: constant Integer := 1000;

  type Queue is private; -- information hiding

  procedure Enqueue (Q: in out Queue, Elem: Integer);
  procedure Dequeue (Q: in out Queue; Elem: out Integer);
  function Empty (Q: Queue) return Boolean;
  function Full (Q: Queue) return Boolean;
  function Slack (Q: Queue) return Integer;
  -- overloaded operator "=":
  function "=" (Q1, Q2: Queue) return Boolean;

private
  ... -- concern of implementation, not of package client
end Queues;
```

# Private parts and information hiding

```
package Queues is
  ... -- visible declarations
private
  type Storage is
    array (Integer range <>) of Integer;
  type Queue is record
    Front: Integer := 0; -- next elem to remove
    Back: Integer := 0;  -- next available slot
    Contents: Storage (0 .. Size-1); -- actual contents
    Num: Integer := 0;
  end record;
end Queues;
```

# Implementation of Queues

```
package body Queues is
  procedure Enqueue (Q: in out Queue;
                     Elem: Integer) is
  begin
    if Full(Q) then
      -- need to signal error: raise exception
    else
      Q.Contents(Q.Back) := Elem;
    end if;
    Q.Num := Q.Num + 1;
    Q.Back := (Q.Back + 1) mod Size;
  end Enqueue;
```

# Predicates on queues

```
function Empty (Q: Queue) return Boolean is
begin
   return Q.Num = 0;    -- client cannot access
                        --   Num directly
end Empty;

function Full (Q: Queue) return Boolean is
begin
   return Q.Num = Size;
end Full;

function Slack (Q: Queue) return Integer is
begin
   return Size - Q.Num;
end Slack;
```

# Operator Overloading

```
function "=" (Q1, Q2 : Queue) return Boolean is
begin
  if Q1.Num /= Q2.Num then
    return False;
  else
    for J in 1 .. Q1.Num loop
      -- check corresponding elements
      if Q1.Contents((Q1.Front + J - 1) mod Size) /=
         Q2.Contents((Q2.Front + J - 1) mod Size)
      then
        return False;
      end if;
    end loop;
    return True; -- all elements are equal
  end if;
end "=";      -- operator "/=" implicitly defined
              --   as negation of "="
```

# Client can only use visible interface

```
with Queues;  use Queues;  with Text_IO;

procedure Test is
  Q1, Q2: Queue; -- local objects of a private type
  Val : Integer;
begin
  Enqueue(Q1, 200); -- visible operation
  for J in 1 .. 25 loop
    Enqueue(Q1, J);
    Enqueue(Q2, J);
  end loop;
  Dequeue(Q1, Val); -- visible operation
  if Q1 /= Q2 then
    Text_IO.Put_Line("lousy␣implementation");
  end if;
end Test;
```

# Implementation

- package body holds bodies of subprograms that implement interface
- package may not require a body:

```
package Days is
  type Day is (Mon, Tue, Wed, Thu, Fri, Sat, Sun);

  subtype Weekday is Day range Mon .. Fri;

  Tomorrow: constant array (Day) of Day
     := (Tue, Wed, Thu, Fri, Sat, Sun, Mon);

  Next_Work_Day: constant array (Weekday) of Weekday
     := (Tue, Wed, Thu, Fri, Mon);
end Days;
```

## Syntactic sugar: `use` and `renames`

Visible entities can be denoted with an expanded name:

```
with Text_IO;
...
Text_IO.Put_Line("hello");
```

`use` clause makes name of entity directly usable:

```
with Text_IO;  use Text_IO;
...
Put_Line("hello");
```

`renames` clause makes name of entity more manageable:

```
with Text_IO;
package T renames Text_IO;
...
T.Put_Line("hello");
```

# Sugar can be indispensable

```
with Queues;

procedure Test is
   Q1, Q2: Queues.Queue;
begin
   if Q1 = Q2 then ...
      -- error: "=" is not directly visible
      -- must write instead: Queues."="(Q1, Q2)
```

Two solutions:

- import all entities:

  ```
  use Queues;
  ```

- import operators only:

  ```
  use type Queues.Queue;
  ```

# C++ namespaces

- late addition to the language
- an entity requires one or more declarations and a single definition
- a namespace declaration can contain both, but definitions may also be given separately

```
// in .h file
namespace util {
  int f (int); /* declaration of f */
}

// in .cpp file
namespace util {
  int f (int i) {
    // definition provides body of function
    ...
  }
}
```

# Dependencies between modules in C++

- files have semantic significance: `#include` directives means textual substitution of one file in another
- convention is to use header files for shared interfaces

```
#include <iostream> // import declarations

int main () {
  std::cout << "C++␣is␣really␣different"
            << std::endl;
  return 0;
}
```

# Header files are visible interfaces

```
namespace stack {  // in file stack.h
  void push (char);
  char pop ();
}
```

---

```
#include "stack.h"  // import into client file

void f () {
  stack::push('c');
  if (stack::pop() != 'c') error("impossible");
}
```

# Namespace Definitions

```
#include "stack.h" // import declarations

namespace stack {  // the definition
  const unsigned int MaxSize = 200;
  char v[MaxSize];
  unsigned int numElems = 0;

  void push (char c) {
    if (numElems >= MaxSize)
      throw std::out_of_range("stack␣overflow");
    v[numElems++] = c;
  }

  char pop () {
    if (numElems == 0)
      throw std::out_of_range("stack␣underflow");
    return v[--numElems];
  }
}
```

# Syntactic sugar: `using` declarations

```
namespace queue { // works on single queue
  void enqueue (int);
  int dequeue ();
}
```

---

```
#include "queue.h"  // in client file

using queue::dequeue;  // selective: a single entity

void f () {
  queue::enqueue(10);  // prefix needed for enqueue
  queue::enqueue(-999);
  if (dequeue() != 10)  // but not for dequeue
    error("buggy␣implementation");
}
```

# Wholesale import: the using directive

```
#include "queue.h"  // in client file

using namespace queue;  // import everything

void f () {
  enqueue(10);  // prefix not needed
  enqueue(-999);
  if (dequeue() != 10)  // for anything
    error("buggy␣implementation");
}
```

# Shortening names

Sometimes, we want to qualify names, but with a shorter name.

In Ada:

```
package PN renames A.Very_Long.Package_Name;
```

In C++:

```
namespace pn = a::very_long::package_name;
```

We can now use `PN` as the qualifier instead of the long name.

# Visibility: Koenig lookup

When an unqualified name is used as the postfix-expression in a function call (**expr.call**), other namespaces not considered during the usual unqualified look up (**basic.lookup.unqual**) may be searched; this search depends on the types of the arguments.

For each argument type T in the function call, there is a set of zero or more associated namespaces to be considered. The set of namespaces is determined entirely by the types of the function arguments. `typedef` names used to specify the types do not contribute to this set.

The set of namespaces are determined in the following way:

# Koenig lookup: details

- If T is a primitive type, its associated set of namespaces is empty.
- If T is a class type, its associated namespaces are the namespaces in which the class and its direct and indirect base classes are defined.
- If T is a union or enumeration type, its associated namespace is the namespace in which it is defined.
- If T is a pointer to U, a reference to U, or an array of U, its associated namespaces are the namespaces associated with U.
- If T is a pointer to function type, its associated namespaces are the namespaces associated with the function parameter types and the namespaces associated with the return type. [recursive]

# Koenig Example

```
namespace NS
{
   class A {};
   void f( A *&, int ) {}
}
int main()
{
   NS::A *a;
   f( a, 0 );    //calls NS::f
}
```

# Linking

- an external declaration for a variable indicates that the entity is defined elsewhere

```
extern int x; // will be found later
```

- a function declaration indicates that the body is defined elsewhere
- multiple declarations may denote the same entity

```
extern int x; // in some other file
```

- an entity can only be *defined* once
- missing/multiple definitions cannot be detected by the compiler: link-time errors

# Modules in Java

- package structure parallels file system
- a package corresponds to a directory
- a class is compiled into a separate object file
- each class declares the package in which it appears (open structure)

```
package polynomials;
class poly {
  ... // in file .../alg/polynomials/poly.java
}
```

---

```
package polynomials;
class iterator {
  ... // in file .../alg/polynomials/iterator.java
}
```

Default: anonymous package in current directory.

# Dependencies between classes

- dependencies indicated with `import` statements:

```
import java.awt.Rectangle; // declared in java.awt

import java.awt.*;     // import all classes
                       //   in package
```

- no syntactic sugar across packages: use expanded names
- none needed in same package: all classes in package are directly visible to each other

# Modules in ML

There are three entities:

- `signature` : an interface
- `structure` : an implementation
- `functor` : a parameterized `structure`

A `structure` implements a `signature` if it defines everything mentioned in the `signature` (in the correct way).

# ML signature

An ML *signature* specifies an interface for a module.

```
signature STACKS =
sig
    type stack
    exception Underflow
    val empty : stack
    val push : char * stack -> stack
    val pop  : stack -> char * stack
    val isEmpty : stack -> bool
end
```

# ML structure

A *structure* provides an implementation.

```
structure Stacks : STACKS =
struct
    type stack = char list
    exception Underflow
    val empty = [ ]
    val push = op::
    fun pop (c::cs) = (c, cs)
      | pop []      = raise Underflow
    fun isEmpty [] = true
      | isEmpty _  = false
end
```

# ML functor

A *functor* creates a structure from a structure.

```
signature TOTALORDER = sig
   type element;
   val lt : element * element -> bool;
end;

functor MakeBST(Lt: TOTALORDER):
sig
    type 'label btree;
    exception EmptyTree;
    val create : Lt.element btree;
    val lookup : Lt.element * Lt.element btree
        -> bool;
    val insert : Lt.element * Lt.element btree
        -> Lt.element btree;
```

# Functors (cont'd)

```
    val deletemin : Lt.element btree ->
        Lt.element * Lt.element btree;
    val delete : Lt.element * Lt.element btree
        -> Lt.element btree;
end = struct
    open Lt;
    datatype 'label btree = Empty |
          Node of 'label * 'label btree * 'label btr
    val create = Empty;
    fun lookup(x, Empty) = ...;
    fun insert(x, Empty) = ...;
    exception EmptyTree;
    fun deletemin(Empty) = ...;
    fun delete(x,Empty) = ...;
end;
```

# Comparisons

```
structure String : TOTALORDER =
  struct
     type element = string;
     fun lt(x,y) =
         let
           fun lower(nil) = nil |
               lower(c::cs) =
                  (Char.toLower c)::lower(cs);
         in
           implode(lower(explode(x))) <
           implode(lower(explode(y)))
         end;
  end;

  structure StringBST = MakeBST(String);
```

# Comparisons

| | Ada | C++ | Java | ML |
|---|---|---|---|---|
| used to avoid name clashes | ✔ | ✔ | ✔ | ✔ |
| access control | ✔ | weak | ✔ | ✔ |
| is closed | ✔ | ✘ | ✘ | ✔ |

Relation between interface and implementation:

- Ada :

  one package (interface) $\Leftrightarrow$ one package body

- ML :

| | | |
|---|---|---|
| one signature | *can be implemented by* | many structures |
| one structure | *can implement* | many signatures |

# Exceptions

General mechanism for handling abnormal conditions

One way to improve robustness of programs is to handle errors. How can we do this?

We can check the result of each operation that can go wrong (e.g., popping from a stack, writing to a file, allocating memory).

Unfortunately, this has a couple of serious disadvantages:

1. it is easy to forget to check
2. writing all the checks clutters up the code and obfuscates the common case (the one where no errors occur)

Exceptions let us write clearer code and make it easier to catch errors.

# Predefined exceptions in Ada

- Defined in `Standard`:
  - `Constraint_Error` : value out of range
  - `Program_Error` : illegality not detectable at compile-time: unelaborated package, exception during finalization, etc.
  - `Storage_Error` : allocation cannot be satisfied (heap or stack)
  - `Tasking_Error` : communication failure
- Defined in `Ada.IO_Exceptions`:
  - `Data_Error`, `End_Error`, `Name_Error`, `Use_Error`, `Mode_Error`, `Status_Error`, `Device_Error`

# Handling exceptions

Any begin-end block can have an exception handler:

```
procedure Test is
  X: Integer := 25;
  Y: Integer := 0;
begin
  X := X / Y;
exception
  when Constraint_Error =>
      Put_Line("did you divide by 0?");
  when others           =>
      Put_Line("out of the blue!");
end;
```

# A common idiom

```
function Get_Data return Integer is
  X: Integer;
begin
  loop
    begin
      Get(X);
      return X;    -- if got here, input is valid,
                   --  so leave loop
    exception
      when others =>
        Put_Line("input must be integer, try again");
         -- will restart loop to wait for a good input
    end;
  end loop;
end;
```

# User-defined Exceptions

```
package Stacks is
  Stack_Empty: exception;
  ...
end Stacks;
```

---

```
package body Stacks is
  procedure Pop (X: out Integer;
                 From: in out Stack) is
  begin
    if Empty(From)
      then raise Stack_Empty;
      else ...
  end Pop;
  ...
end Stacks;
```

# The scope of exceptions

- an exception has the same visibility as other declared entities: to handle an exception it must be visible in the handler (e.g., caller must be able to see `Stack_Empty`).
- an `others` clause can handle unnamed exceptions

```
when others =>
  Put_Line("disaster somewhere");
  raise;    -- propagate exception,
            --  program will terminate
```

# Exception run-time model

How to propagate an exception:

1. When an exception is raised, the current sequence of statements is abandoned (e.g., current `Get` and `return` in example)
2. Starting at the current frame, if we have an exception handler, it is executed, and the current frame is completed.
3. Otherwise, the frame is discarded, and the enclosing *dynamic* scopes are examined to find a frame that contains a handler for the current exception (want dynamic as opposed to static scopes because those are values that caused the problem).
4. If no handler is found, the program terminates.

Note: The current frame is never resumed.

# Exception information

- an Ada exception is a label, not a value: we cannot declare exception variables and then assign to them
- but an exception *occurrence* is a value that can be stored and examined
- an exception occurrence may include additional information: source location of occurrence, contents of stack, etc.
- predefined package `Ada.Exceptions` contains needed machinery

# Ada.Exceptions (part of std libraries)

```
package Ada.Exceptions is
  type Exception_Id is private;
  type Exception_Occurrence is limited private;

  function Exception_Identity (X: Exception_Occurrence)
    return Exception_Id;
  function Exception_Name (X: Exception_Occurrence)
    return String;

  procedure Save_Occurrence
    (Target: out Exception_Occurrence;
     Source: Exception_Occurrence);
  procedure Raise_Exception (E: Exception_Id;
                             Message: in String := "")
  ...
end Ada.Exceptions;
```

# Using exception information

```
begin
   ...
exception
   when Expected: Constraint_Error =>
      -- Expected has details
      Save_Occurrence(Event_Log, Expected);

   when Trouble: others =>
      Put_Line("unexpected␣" &
               Exception_Name(Trouble) &
               "␣raised");
      Put_Line("shutting␣down");
      raise;
end;
```

# Exceptions in C++

- similar *runtime* model,...
- but exceptions are bona-fide values,
- handlers appear in `try/catch` blocks

```
try {
  some_complex_calculation();
} catch (const RangeError& e) {
  // RangeError might be raised
  //  in some_complex_calculation
  cerr << "oops\n";
} catch (const ZeroDivide& e) {
  // same for ZeroDivide
  cerr << "why␣is␣denominator␣zero?\n";
}
```

# Defining and throwing exceptions

The program throws an object. There is nothing needed in the declaration of the type to indicate it will be used as an exception.

```
struct ZeroDivide {
  int lineno;
  ZeroDivide (...) { ... }  // constructor
  ...
};


...
if (x == 0)
  throw ZeroDivide(...);    // call constructor
                             //  and go
```

# Exceptions and inheritance

A handler names a class, and can handle an object of a derived class as well:

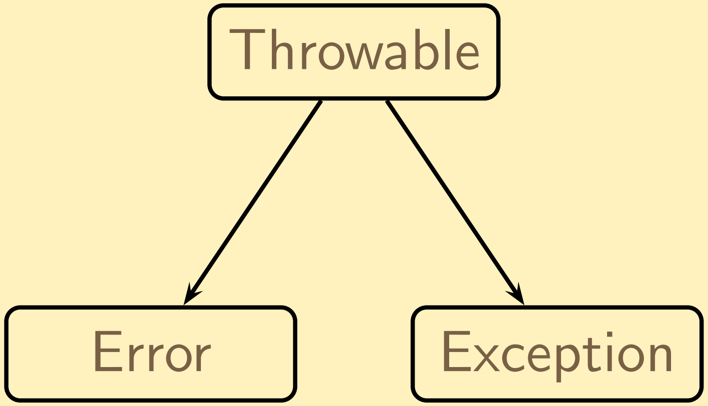
```
class Matherr { }; // a bare object, no info
class Overflow : public Matherr {...};
class Underflow : public Matherr {...};
class ZeroDivide : public Matherr {...};

try {
  weatherPredictionModel(...);
} catch (const Overflow& e) {
  // e.g., change parameters in caller
} catch (const Matherr& e) {
  // Underflow, ZeroDivide handled here
} catch (...) {
  // handle anything else (ellipsis)
}
```

# Exceptions in Java

- Model and terminology similar to C++:
  - exceptions are objects that are thrown and caught
  - `try` blocks have handlers, which are examined in succession
  - a handler for an exception can handle any object of a derived class
- Differences:
  - all exceptions are extensions of predefined class `Throwable`
  - checked exceptions are part of method declaration
  - the `finally` clause specifies clean-up actions
    - in C++, cleanup actions are idiomatically done in destructors

# Exception class hierarchy




- System errors are extensions of `Error` and `RuntimeException`; these are *unchecked* exceptions. Examples: `ClassCastException`, `NullPointerException`, `OutOfMemoryError`.
- All other exception classes are *checked*. These exceptions must be either handled or declared in the method that throws them; this is checked by the compiler.

# If a method might throw an exception, callers should know about it

```
public void replace (String name,
                     Object newValue) throws NoSuch
{
   Attribute attr = find(name);
   if (attr == null) throw new NoSuch(name);
   newValue.update(attr);
}
```

# Mandatory cleanup actions

Some cleanups must be performed whether the method terminates normally or throws an exception.

```
public void parse (String file) throws IOException {
  BufferedReader input =
    new BufferedReader(new FileReader(file));
  try {
    while (true) {
      String s = input.readLine();
      if (s == null) break;
      parseLine(s);  // may fail somewhere
    }
  } finally {
    if (input != null) input.close();
  }  //regardless of how we exit
}
```

# Exceptions in ML

- runtime model similar to Ada/C++/Java
- `exception` is a single type (like a `datatype` but dynamically extensible)
- declaring new sorts of exceptions:

```
exception StackUnderflow
exception ParseError of { line: int, col: int }
```

- raising an exception:

```
raise StackUnderflow
raise (ParseError { line = 5, col = 12 })
```

- handling an exception:

  $expr_1$ `handle` *pattern* `=>` $expr_2$

  If an exception is raised during evaluation of $expr_1$, and *pattern* matches that exception, $expr_2$ is evaluated instead

# A closer look

```
exception DivideByZero

fun f i j =
  if j <> 0
    then i div j
    else raise DivideByZero
```

---

```
(f 6 2
 handle DivideByZero => 42)    (* evaluates to 3 *)
```

---

```
(f 4 0
 handle DivideByZero => 42)    (* evaluates to 42 *)
```

Typing issues:

- the type of the body and the handler must be the same
- the type of a `raise` expression can be *any type* (whatever type is appropriate is chosen)